9pm Cutoff 256x256 GaAs/Al$_x$Ga$_{1-x}$As Quantum Well Infrared Photodetector Focal Plane Array Camera

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ABSTRACT

In this paper, we discuss the development of very sensitive long wavelength infrared (LWIR) GaAs/Al$_x$Ga$_{1-x}$As quantum well infrared photodetectors (QWIPs), fabrication of random reflectors for efficient light coupling, and the demonstration of a LWIR 256x 256 focal plane array imaging camera. Excellent imagery, with a noise equivalent differential temperature (NEAT) of 25 mK has been achieved.

1NTRODUCTION

There are several applications that require long wavelength, large, uniform, reproducible, low cost, low 1/f noise, low power dissipation, and radiation hard infrared (IR) focal plane arrays (FPAs). For example, the absorption lines of many gas molecules, such as ozone, water, carbon monoxide, carbon dioxide, and nitrous oxide occur in the wavelength region from 3 to 18 pm. Thus, IR imaging systems that operate in the long wavelength IR (LWIR) region (6-18 pm) are required in many space applications such as monitoring the global atmospheric temperature profiles, relative humidity profiles, cloud characteristics, and the distribution of minor constituents in the atmosphere which are being planned for NASA's Earth Observing System [1]. In addition, 8 - 15 µm FPAs would be very useful in detecting cold objects such as ballistic missiles in midcourse (when a hot rocket engine is not burning most of the emission peaks are in the 8-15 µm IR region) [2]. The GaAs based Quantum Well Infrared Photodetector (QWIP) [3,4,5] is a potential candidate for such spaceborne and ground based applications and it can meet all of the requirements mentioned above for this spectral region.

Fig. 1 shows the schematic conduction band diagram of a typical *bound-to-continuum* QWIP [6] which utilizes bound-to-continuum intersubband absorption. By carefully 'designing the quantum well structure, as well as the light coupling to the detector, it is possible to optimize the material to have an optical response in the desired spectral range and determine the spectral response shape [7]. In QWIPs, the dark current originates from three different mechanisms [8]. As shown in Fig. 1, the dark current arising from the first process is due to quantum mechanical tunneling from well to well through the Al$_x$Ga$_{1-x}$As barriers (sequential tunneling). This process is independent of temperature. Sequential tunneling dominates the dark current at very low

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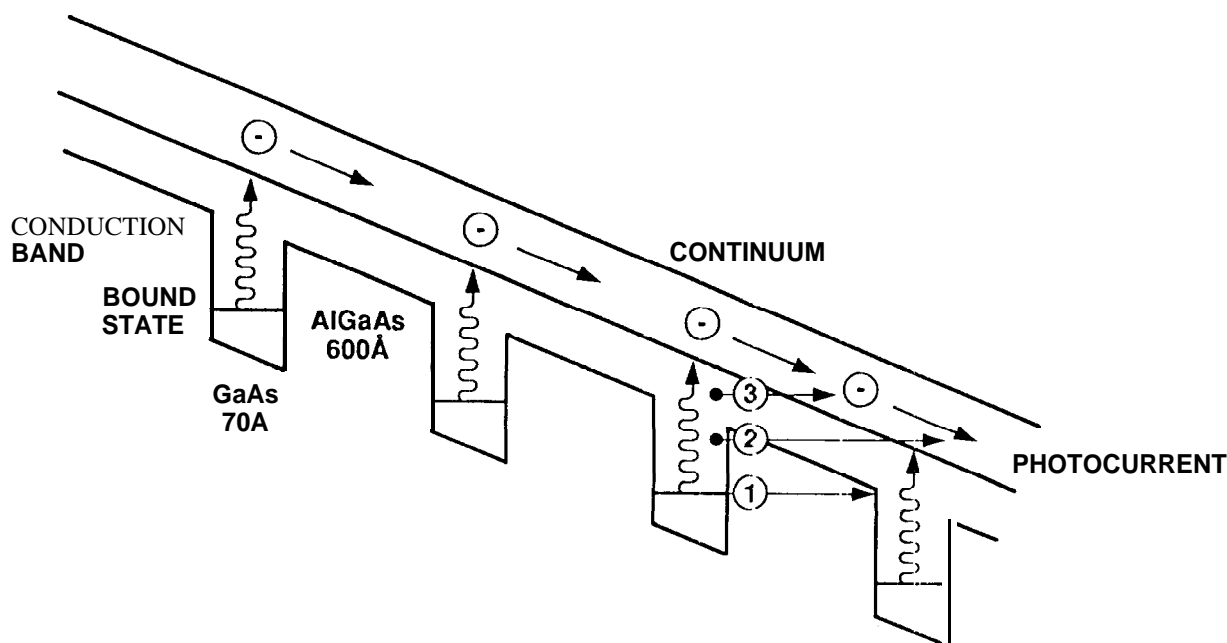\#   Present address: elop-Electroptics Industries Ltd., Rehovot 76111 Israel

Fig, 1 Schematic diagram of the conduction band in a bound-to-continuum QWIP with an electric field. Absorption of IR photons can photoexcite electrons from the ground state of the quantum well into the continuum, causing a photocurrent. Three dark current mechanisms are also shown: ground state tunneling (1); thermally assisted tunneling (2); and thermionic emission (3).
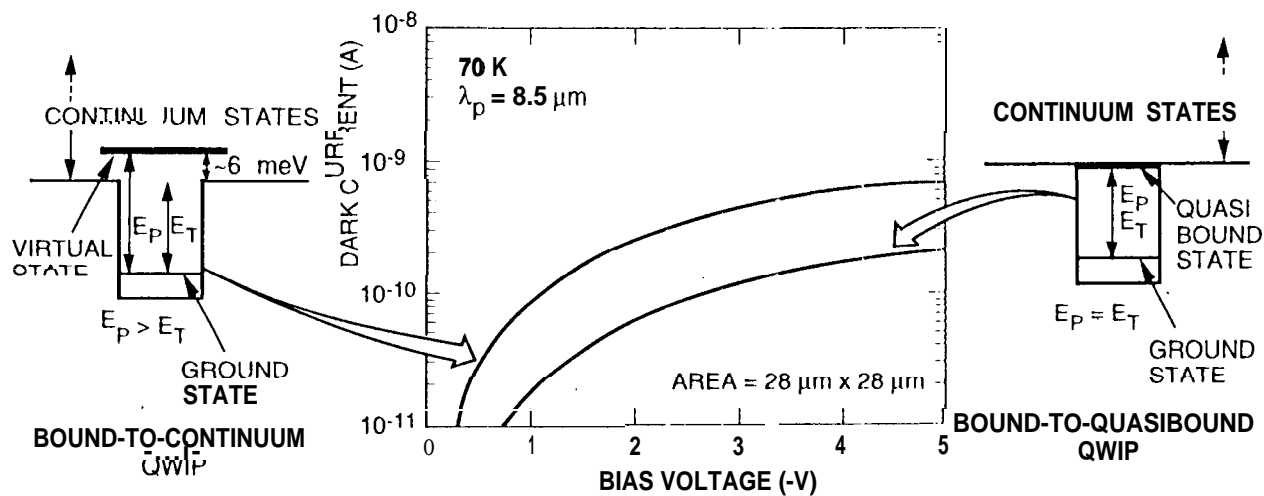

Fig. 2 Comparison of dark currents of bound-to-continuum and bound-to-quasibound LWIR QWIPs as a function of bias voltage at temperature T =70 K. Data were taken with a 200 μm diam test structure and normalized to 28x28 μm² pixel.

temperatures (<30 K). The second mechanism is thermally assisted tunneling which involves a thermal excitation and tunneling through the tip of the barrier into the continuum energy levels. This process governs the dark current at medium temperatures. The third mechanism is classical thermionic emission and it dominates the dark current at higher temperatures (>55 K for 9 μm cutoff QWIPs). Consequent] y, for QWIPs operating at higher temperatures the last mechanism is the major source of dark current [8]. Therefore, the LWIR FPA we have discussed here in detail consisted of *bound-to-quasibound* QWIPs [9]. The advantage of the bound-toquasibound QWIP over the bound-to-continuum QWIP [9] is that in the case of a bound-to-quasibound QWIP the energy barrier for thermionic emission is the same as it is for photoionization as shown in Fig. 2. In the case of the bound-to-continuum QWIP shown in Fig. 2 the energy barrier for the thermionic emission is about 6 meV less than the photoionization energy. Thus, the dark current of bound-to-

quasibound QWIPs is reduced by a factor of 3 (i.e., $I_d \propto e^{-}: \approx e^{-1}$ for T =70 K) compared with bound-to-continuum QWIPs operating at the same peak wavelength.

TEST STRUCTURE RESULTS

The device structure consists of 50 periods, each period containing a 45 Å well of GaAs (doped n = 4×10^{17} cm^{-3}) and a 500 Å barrier of $Al_{0.3}Ga_{0.7}As$, sandwiched between 0.5 μm GaAs top and bottom contact layers doped n = 5×10^{17} cm^{-3}, grown on a semi-insulating GaAs substrate by molecular beam epitaxy (MBE). Then a 0.7 μm thick GaAs cap layer on top of a 300 Å $Al_{0.3}Ga_{0.7}As$ stop-etch layer was grown *in situ* on top of the device structure to fabricate the light coupling optical cavity. The MBE grown QWI P structure was processed into 200 μm diameter mesa test structures (area = 3.14×10^{-4} cm^2) using wet chemical etching, and Au/Ge ohmic contacts were evaporated onto the top and bottom contact layers, The dark current-voltage curves of the QWIP were measured as a function of temperature from T = 30-90 K and the T = 70 K **curve**
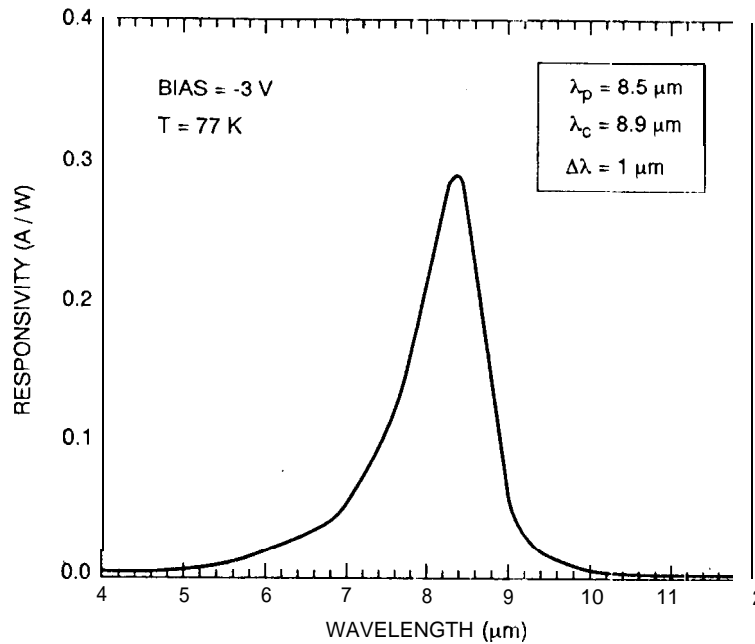

Fig. 3 Responsivity spectrum of a bound-to-quasibound LWIR QWIP test structure at temperature T = 77 K. The spectral response peak is at 8.5 μm and the long wavelength cutoff is at 8.9 pm.

is shown in Fig. 2 with the dark current-voltage curve of a 8.5 μm peak bound-to-continuum QWIP. The virtual excited level of this bound-to-continuum QWIP is 6 meV above the $Al_xGa_{1-x}As$ barrier. Theoretically this should give a factor of 3 higher dark current and it closely agrees with the experimental value of a factor of 4 higher dark current at bias $V_B = -2V$.

The responsivity spectra of these detectors were measured using a 1000 K blackbody source and a grating monochromator. The absolute peak responsivities R_p of the detectors were measured using a calibrated blackbody source, The detectors were back illuminated through a 45" polished facet [7] and a responsivity spectrum is shown in Fig. 3. The responsivity of the detector peaks at 8.5 μm and the peak responsivity (R_p) of the detector is 300 mA/W at bias $V_B = -3$ V. The spectral width and the cutoff wavelength are $\Delta\lambda / \lambda = 10\%$ and $\lambda_c = 8,9$pm respectively. The bias dependent peak responsivity of the detector is shown in Fig. 4. The measured absolute peak responsivity of the detector is small up to about $V_B = -0.5$ V. Beyond that it increases nearly linearly with bias reaching Rp = 380 mA/W at $V_B = -5$ V. This type of behavior of responsivity versus bias is typical for a bound-to-quasibound QWIP. The peak quantum efficiency was 7% at bias $V_B = -1$ V (lower quantum efficiency is due to the lower well doping density) for a 45° double pass.

The current noise i_n was measured using a spectrum analyzer and the photoconductive gain g was experimentally determined using [10] $g = i_n^2 / 4eI_DB + 1/2N$, where B is the measurement band width and N is the number of quantum wells. The photoconductive gain of the detector reached 0,98 at $V_B = -5$ V. Since the gain of QWIP is inversely proportional to the number of quantum wells N, the better comparison would be the well capture probability p_c, which is directl y related to the gain [11] by $g = 1/Np_c$. The calculated well capture probabilities are 25 % at
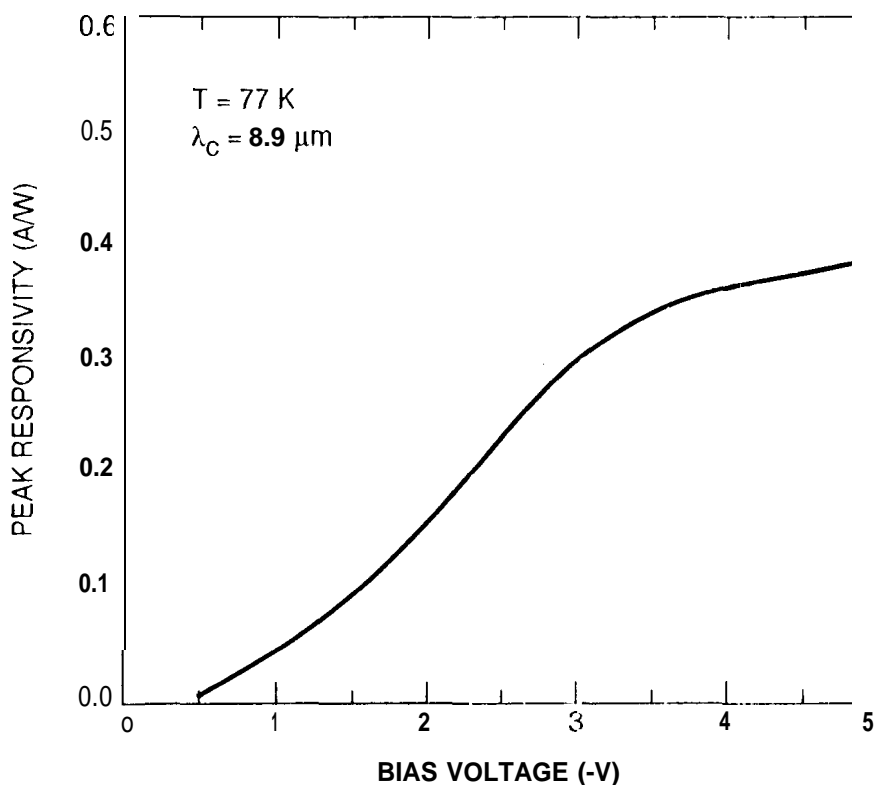

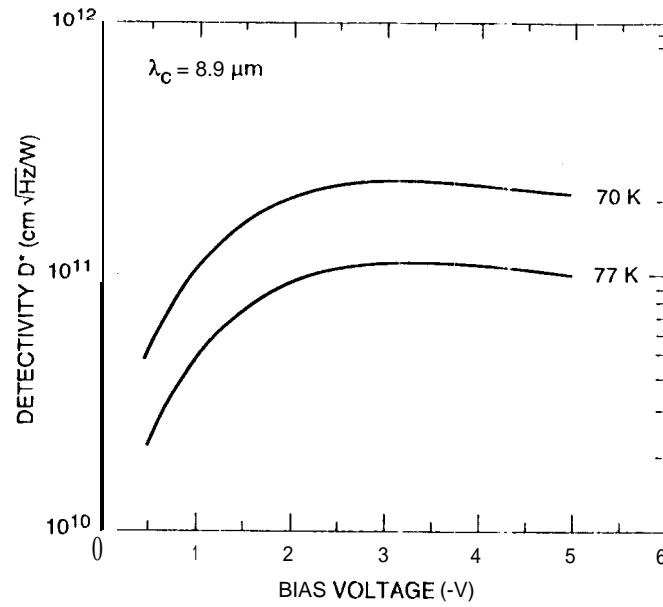Fig. 4 Peak responsivity as a function of bias voltage at temperature T = 77 K.

Fig. 5 Defectivity as a function of bias voltage at temperatures T = 70 and 77 K.
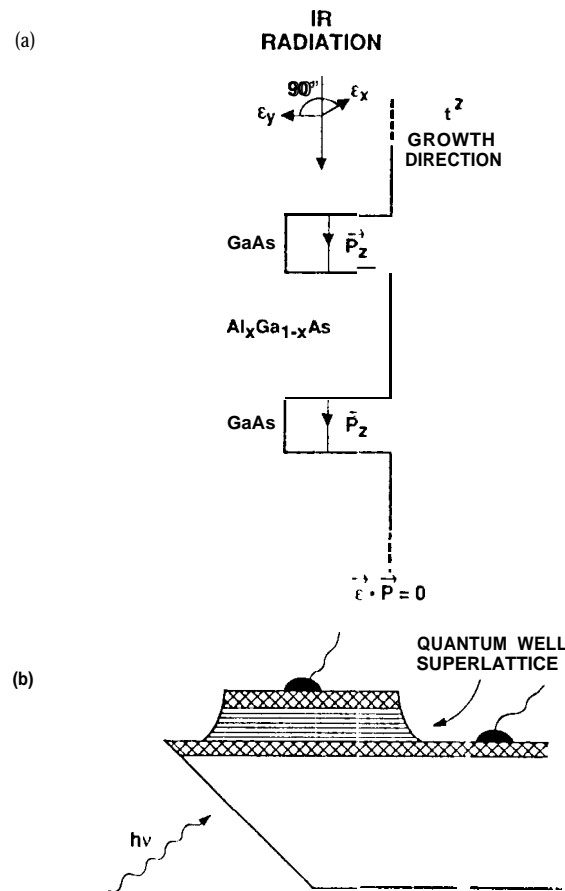

Fig. 6 (a) Intersubband absorption process of QWIPs at normal incidence. (b) 45" polished facet light coupling.

low bias (i.e., V_B = -1 V) and 2% at high bias (i.e., V_B = -5 V) which together indicate the excellent hot-electron transport in this device structure. The peak defectivity is defined as $D_P^* = R_P \sqrt{AB} / i_n$, where Rp is the peak responsivity, A is the area of the detector and A = 3,14x1 0^4cm^2. The measured peak defectivity at bias V_B = -3.2 V and temperature T = 70 K is 2.3x10^{11} cm√Hz/W.

LIGHT COUPLING

QWIPs do not absorb radiation incident normal to the surface since the light polarization must have an electric field component normal to the superlattice (growth direction) to be absorbed by the confined carriers. As shown in Fig. 6(a) when the incoming light contains no polarization component along the growth direction, the matrix element of the interaction vanishes (i.e., $\vec{\varepsilon}.\vec{p}_z$ =0 where $\vec{\varepsilon}$ is the polarization and $\vec{p}_z$ is the momentum along the z direction). As a consequence, these detectors have to be illuminated through a 45" polished facet [7] as shown in Fig. 6(b). Clearly, this illumination scheme limits the configuration of detectors to linear arrays and single elements, For imaging, it is necessary to be able to couple light uniformly to two dimensional arrays of these detectors.

Many more passes of IR light inside the detector structure can be obtained by incorporating a randomly roughened reflecting surface on top of the detectors which also removes the light coupling limitations and makes two dimensional QWIP imaging arrays feasible. A factor of eight enhancement in QWIP responsivity compared to 45" illumination geometry has been achieved with a randomly roughened reflecting surface [11]. The random structure on top of the detector prevents the light from being diffracted normally backward after the second bounce as happens in the case of cross-grating. After each bounce, light is scattered at a. different random angle and the only chance for light to escape out of the detector is when it is reflected towards the surface within the critical angle of the normal, For the GaAs/air interface this angle is about 17°, defining a very narrow escape cone for the trapped light. The reflector was designed with two levels of scattering surfaces located at quarter wavelength separations, as shown in Fig. 7. The area of the top unetched
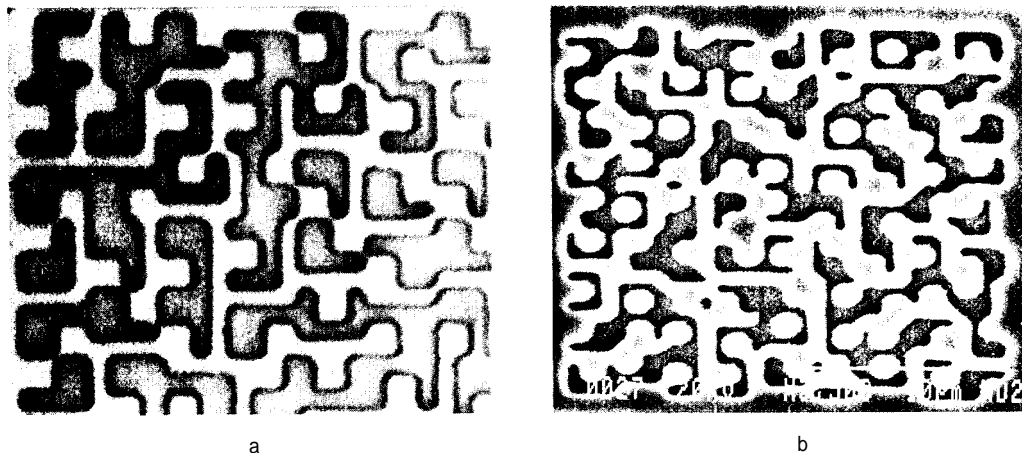

a   b

Fig. 7 (a) Two level random reflector on a pixel (38x38 μm^2) of 15 μm cutoff QWIP FPA. The minimum feature size is 1.25 pm. (b) Two level random reflector on a pixel (28x28 μm^2) of 9 μm cutoff QWIP FPA. The minimum feature size is 0.6μm. This random reflector was less sharp and had fewer scattering centers when compared to Fig. 7(a) due to the difficulties associated with sub-micron photolithography.

level is equal to the area of the etched level ($\lambda_{GaAs}/4$ deep). Therefore, the normally reflected light intensities from the top and bottom surfaces of random reflector are equal and 180° out of phase, thus maximizing the destructive interference at normal reflection and hence lowering the light leakage through the escape cone. This random structure was fabricated on the detectors by using standard photolithography and CCl_2F_2 selective dry etching. The advantage of the photolithographic process over a completely random process is the ability to accurately control the feature size and preserve the pixel to pixel uniformity which is a prerequisite for high sensitivity imaging FPAs.

IMAGING ARRAYS

Figures 7(a) and 7(b) show random reflectors on a pixel of 15μm cutoff 128x128 and 9 μm cutoff 256x256 QWIP FPAs respectively. The minimum feature size of the random reflectors of 15 μm cutoff and 9 μm cutoff FPAs were 1.25 and 0.6 μm respectively. As shown in Fig. 7(b) the random reflectors of the 9 μm cutoff FPA were less sharp and had fewer scattering centers compared to Fig. 7(a) and this is due to the difficulties associated with sub-micron photolithography. After the random reflector array was defined by the lithography and dry etching, the photoconductive QWIPs of the 256x256 FPAs were fabricated by wet chemical etching through the photosensitive $GaAs/Al_xGa_{1-x}As$ multi-quantum well layers into the 0.5 μm thick doped GaAs bottom contact layer. The pitch of the FPA is 38 μm and the actual pixel size is 28x28 μm^2. Then the random reflectors on top of the detectors were covered with Au/Ge and Au for Ohmic contact and reflection. Figure 8 shows twenty five processed QWIP FPAs on a 3 inch GaAs wafer. Then iridium bumps were evaporated on top of the detectors for Si readout circuit (ROC) hybridization. A single QWIP FPA was chosen and hybridized (via iridium bump-bonding process) to a 256x256 Si multiplexer (Amber AE- 166) and biased at $V_B = -1.0$ V. The FPA was back-illuminated through the flat thinned substrate membrane (thickness ≈ 1300 Å). This initial array gave excellent images with 99.98% of the pixels working (number of dead pixels $\approx$ 10) , demonstrating the high yield of GaAs technology.

We have used the following equation to calculate the noise equivalent temperature difference NEAT of the FPA.
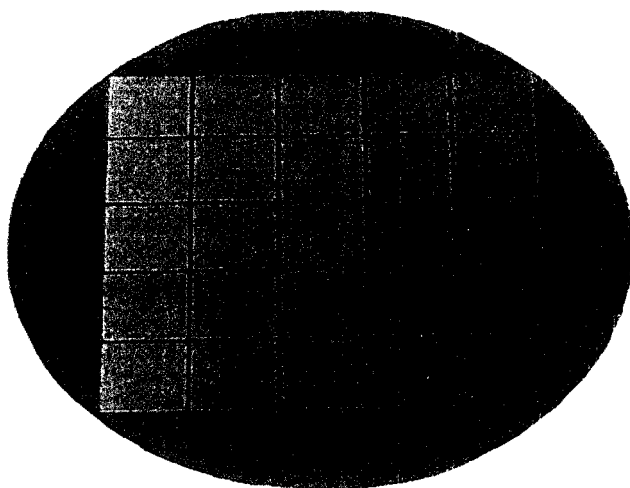

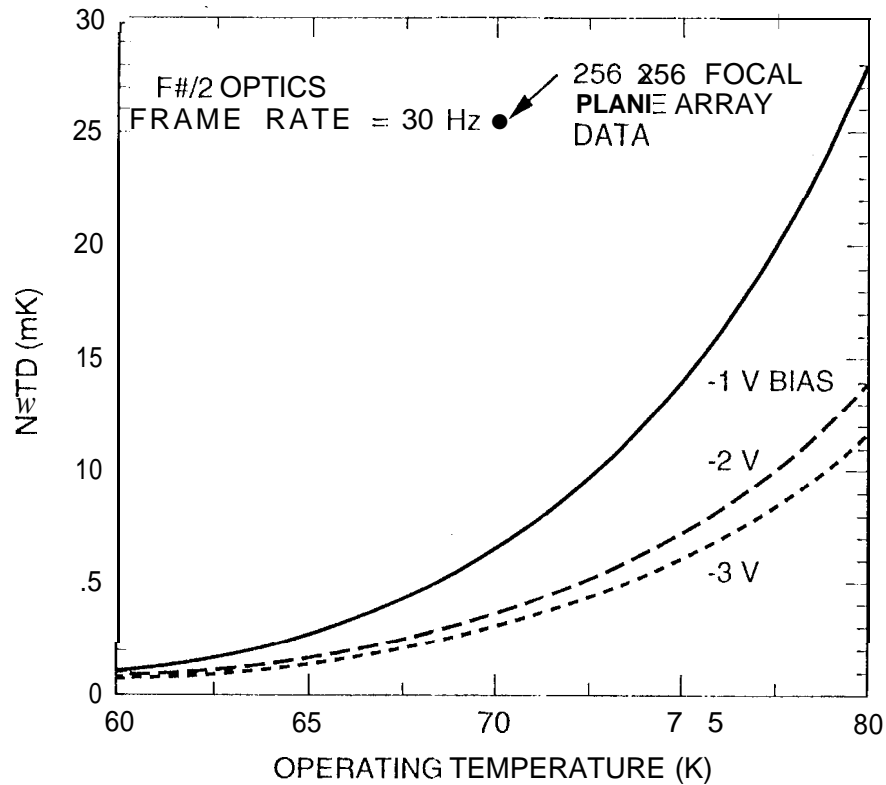Fig. 8 Twenty five 256x256 QWIP focal plane arrays on a 3 in. GaAs wafer.

Fig. 9 Noise equivalent temperature difference NEAT estimated from test structure data as a function of temperature for bias voltages V_B = -1, -2, and -3 V. The background temperature T_B = 300 K and the area of the pixel A = (28 μm)^2. The measured NEAT of the focal plane array is 25 mK at an operating temperature of 70 K and bias V_B = -1 V.
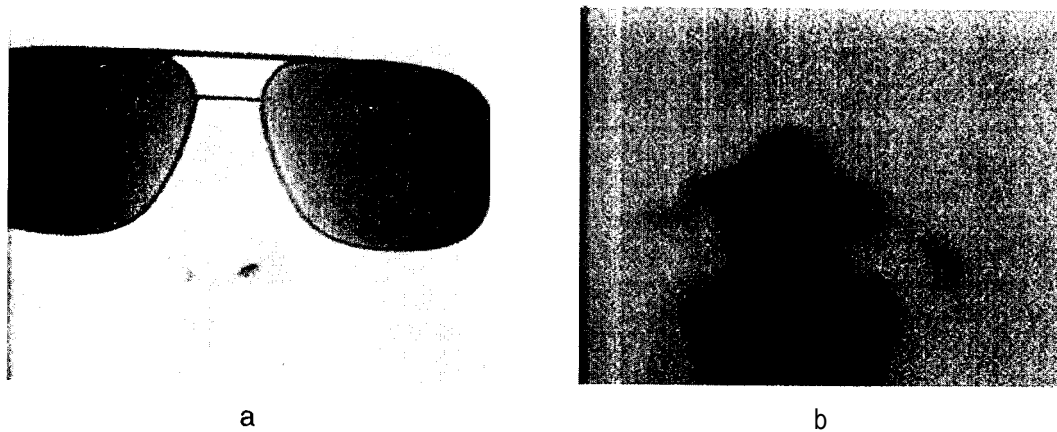

Fig. 10 (a) One frame of video image taken with the 9 pm cutoff 256x256 QWIP camera, The tiny dark squares on each frame of the glasses are the reflections of coldFPA in the camera, (b) An absorption image of acetone fumes (acetone has a strong IR absorption at 8.8μm) taken with a 9 μm cutoff 256x256 QWIP FPA camera.

$$NE\Delta T = \frac{\sqrt{AB}}{D_B^{*}(dP_B / dT)}$$

(1)

where D_B^{*} is the blackbody defectivity and dP_B / dT is the derivative of the integrated blackbody power with respect to temperature. Figure 9 shows the NEAT of the FPA estimated from the test structure data as a function of temperature for bias voltages V_B = -1, -2, and -3 V and the frame rate of 30 Hz. The background temperature T_B = 300 K and the area of the pixel A = (28 µm)^2. The measured mean NFAT of the FPA was 25 mK at an operating temperature of T = 70 K and bias V_B = -1 V for 300 K background. This reasonably agrees with our estimated value of 7 mK based on test structure data, The peak quantum efficiency of the FPA was 9.5% (much lower quantum efficiency than expected can be attributed to the poor grating fill factor) and this corresponds to an average of 3 passes of IR radiation through the photosensitive multi-quantum well region. The uncorrected photocurrent uniformity (pixel-to-pixel) of the 65,536 pixels of the 256x256 FPA is about 7% (= sigma/mean). The uniformit y after two point (17" and 27° Celsius) correction was 0.05 %. As mentioned earlier this high yield is due to the excellent GaAs growth uniformity and the mature GaAs processing technology.

Video images were taken at a frame rate of 30 Hz with f/2 anti-reflection coated germanium optics at temperatures as high as T = 70 K, using a ROC capacitor having a charge capacity of 9x1@ electrons. Figure 10 (a) shows one frame of a video image taken with a 9 µm cutoff 256x256 QWIP camera. The 2 tiny dark squares on the glasses are the reflections of cold FPA of the camera. Figure 10(b) shows an absorption image of acetone fumes (acetone has a strong IR absorption at 8.8 µm) taken with the same camera. These images demonstrate the high sensitivity of the **256x256** QWIP staring array camera,

No band pass filters were used and are unnecessary in QWIP camera systems because of the narrow spectral response of QWIPs. It should be noted that these initial unoptimized FPA results are far from optimum. The gratings were not optimized (as described earlier) for maximum light coupling efficiency; no microlenses were used; no antireflection coatings were used on the backside of the FPA; and finally the multiplexer used was a photovoltaic InSb multiplexer which is certainly not optimized to supply the proper bias and impedance levels required by photoconductive QWIPs. Implementation of these improvements should significantly enhance the QWIP FPA operating temperature (i.e., 77 K for 9 pm).

ACKNOWLEDGMENTS

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The current noise i_n was measured using a spectrum **anal yzer and the** photoconductive gain g was experimentally determined using [10] g. i_n^2 / $4eI_DB$ + 1/2N, where B is the measurement band width and N is the number of quantum wells. The photoconductive gain of the detector reached 0.98 at V_B =-5 V, Since the gain of QWIP is inverse] y proportional to the number of quantum wells N, the better comparison would be the well capture probability p_c, which is directly related to the gain [11] by g = 1/Np_c. The calculated wc]] capture probabilities are 25% at low bias (i.e., V_B = -1 V) and 2% at high bias (i.e., V_B = -5 V) which together indicate the excellent hot-electron transport in this device structure. The peak defectivity is defined as $D_p^* = R_p \sqrt{AB}$ / i_n, where Rp is the peak responsivit y, A is the area of the detector and A = 3.14x10-4 cm^2. The measured peak detectivity at bias V_B = -3.2 V and temperature T = 70 K is 2.3x10^{1}1 cm√Hz/W. These detectors show background limited performance (BLI P) at bias V_B = -2 V and temperature T =72 K for 300 K background with f/2 optics.

light Coupling

QWIPs do not absorb radiation incident normal to the surface since the light polarization must have an electric field component normal to the superlattice (growth direction) to be absorbed by the confined carriers. As shown in Fig. 6(a) when the incoming light contains no polarization component along the growth direction, the matrix clement of the interaction vanishes (i.e., $\vec{\varepsilon}.\vec{p}_z$ =0 where $\vec{\varepsilon}$ is the polarization and $\vec{p}_z$ is the momentum along the z direction). As a consequence, these detectors have to be illuminated through a 45° polished facet [7] as shown in Fig. 6(b). Clearly, this illumination scheme limits the configuration of detectors to linear arrays and single elements. For imaging, it is necessary to be able to couple light uniformly to two dimensional arrays of these detectors.

Many more passes of IR light inside the detector structure can be obtained by incorporate ing a randomly roughened reflecting surface on top of the detectors which also removes the light coupling limitations and makes two dimensional QWIP imaging arrays feasible. A factor of eight enhancement in QWIP responsivity compared to 45" il I umination geometry has been achieved with a random] y roughened reflecting surface [11]. The random structure on top of the detector prevents the light from being diffracted

normally backward after the second bounce as happens in the case of cross-grating. After each bounce, light is scattered at a different randomangle and the only chance for light to escape out of the detector is when it is reflected towards the surface within the critical angle of the normal. For the GaAs/air interface this angle is about 17°, defining a very narrow escape cone for the trapped light. The reflector was designed with two levels of scattering surfaces located at quarter wavelength separations, as shown in Fig. 7. The area of the top unetched level is equal to the area of the etched level ($\lambda_{GaAs}/4$ deep). Therefore, the normally reflected light intensities from the top and bottom surfaces of random reflector are equal and 180° out of phase, thus maximizing the destructive interference at normal reflection and hence lowering the light leakage through the escape cone. 'l'his random structure was fabricated on the detectors by using standard photolithography and CCl_2F_2 selective dry etching. The advantage of the photo]ithographic process over a completely random process is the ability to accurately control the feat urc si ze and preserve the pixel to pixel uniformity which is a prerequisite for high sensitivity imaging FPAs.

imaging Arrays

Figures 7(a) and 7(b) show random reflectors on a pixel of 15 µm cutoff 128x128 and 9 µm cutoff 256x256 QWIP FPAs respectively. The minimum feature size of the random reflectors of 15 µm cutoff and 9 µm cutoff FPAs were 1.25 and 0.6 µm respectivel y. As shown in Fig. 7(b) the random reflectors of the 9 µm cutoff FPA were less sharp and had fewer scattering centers compared to Fig. 7(a) and this is due to the difficulties associated with sub-micron photolithography. After the random reflector array was defined by the lithography and dry etching, the photoconductive QWIPs of the 256x256 FPAs were fabricated by wet chemical etching through the photosensitive $GaAs/Al_xGa_{1-x}As$ multi-quantum well. layers into the 0.5 µm thick doped GaAs bottom contact layer. The pitch of the FPA is 38 µm and the actual pixel size is 28x28 µm². Then the random reflectors on top of the detectors were covered withAu/Ge and Au for Ohmic contact and reflection. Figure 8 shows twenty five processed QWI P FPAs on a 3 inch GaAs wafer. Then iridium bumps were evaporated on top of the detectors for Si readout circuit (ROC) hybridization. A single QWIP FPA was chosen and hybridized (via iridium bump-bonding process) to a 256x256 CMOS multiplexer (Amber AR-166) and biased at $V_B = -1.0$ V. At temperatures below 72 K, the signal to noise ratio of the system is limited by array non-uniformity, multiplexer readout noise, and photo current (photon flux) noise. At temperatures above 72 K, temporal noise due to the QWI P's higher dark

current becomes the limitation. As mentioned earlier this higher dark current is due to thermionic emission and which causes the charge storage capacitors of the readout **circuitry to saturate. Since** the QWI P is a high impedance device, it should yields a very high charge injection coupling efficiency into the integration capacitor of the multiplexer. If fact Bethea *et al.* [3] have demonstrated charge injection efficiencies approaching 90%. Charge injection efficiency can be obtained from [4]

$$\eta_{inj} = \frac{g_m R_{Det}}{1 + g_m R_{Det}} \left[1 + \frac{1}{1 + \frac{i \omega C_{Det}}{1 + g_m R_{Det}}} \right] \tag{1}$$

where g_m is the transconductance of the MOSFET and it is given by $g_m = eI_{Det}/kT$. The differential resistance R_{Det} of the pixels at -1 V bias is 4.5×10^{10} Ohms at T=70 K and detector capacitance C_{Det} is 3.0×10^{-14} F. The detector dark current $I_{Det} = 14$ pA at same operation condition. According to the equation (1) the charge injection efficiency $\eta_{inj}=99\%$ at a frame rate of 30 Hz. The FPA was back-illuminated through the flat thinned substrate membrane (thickness ≈ 1300 Å). This initial **array gave excellent** images with 99.98% of the pixels working (number of dead pixels ≈ 10) , demonstrating the high yield of GaAs technology.

We have used the following equation to calculate the noise equivalent temperature difference NEΔT of the FPA.

$$NE\Delta T = \frac{\sqrt{AB}}{D_B^* (dP_B / dT) \sin^2 (O/2)} \tag{2}$$

where D_B^* is the blackbody detectivity, dP_B / dT is the derivative of the integrated blackbody power with respect to temperature, and θ is the field of view angle [i.e., $\sin^2(\theta /2) = (4f^2+1)^{-1}$, where f is the f number of the optical system]. Figure 9 shows the NEAT of the FPA estimated from the test structure data as a function of temperature for bias voltages $V_B = -1, -2$, and -3 V. The background temperature $T_B = 300$ K, the area of the pixel A = $(28 \mu m)^2$, the f number of the optical system is 2, and the frame rate is 30 Hz. The measured mean NEΔT of the FPA was 25 mK at an operating temperature of T = 70 K and bias $V_B = -1$ V for 300 K background. This reasonably agrees with our estimated value of 7 mK based on test structure data. The peak quantum efficiency of the FPA was 3 % (much lower quantum efficiency than expected can be attributed to the poor

grating fill factor) and this corresponds to an average of 3 passes of IR radiation (equivalent to single 45° pass) through the photosensitive multi-quantum well region, As shown in Fig. 10 the uncorrected photocurrent non-uniformity (which include 1 % non-uniformity of ROC and 1.4% non-uniformity due to the cold-stop not being able give the same field of view to all the pixels in the FPA) of the 65,536 pixels of the 256x256 FPA is about 6.8% (= sigma/mean). The non-uniformity after two point (1 '7° and 27" Celsius) correction was 0.05%, As mentioned earlier this high yield is due to the excellent GaAs growth uniformity and the mature GaAs processing technology.

Video images were taken at a frame rate of 30Hz with f/2 anti-reflection coated germanium optics at temperatures as high as T =: 70 K, using a ROC capacitor having a charge capacity of $9x10^6$ electrons. Figure 11(a) shows one frame of a video image taken with a 9 µm cutoff 256x256 QWIP camera. The 2 tiny dark squares on the glasses are the reflections of cold FPA of the camera. Figure 10(b) shows an absorption image of **acetone** fumes (acetone has a strong IR absorption at 8.8 pm) taken with the same camera. These images demonstrate the high sensitivity y of the 256x256 QWI P staring array camera.

No band pass filters were used and are unnecessary in QWI P camera systems because of the narrow spectral response of QWIPs. It should be noted that these initial unoptimized FPA results are far from optimum. The gratings were not optimized (as described earlier) for maximum light coupling efficiency; no microlenses were used; no antireflection coatings were used on the backside of the FPA; and final] y the multiplexer used was a photovoltaic InSb multiplexer which is certainly not optimized to supply the proper bias and impedance levels required by photoconductive QWIPs. implementation of these improvements should significant y enhance the QW1 P FPA operating temperature (i.e., 77 K for 9 pm).

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FIGURE CAPTIONS

Fig. 1 Schematic diagram of the conduction band in a bound-to-continuum QWIP with an electric field. Absorption of 1 R photons can photoexcite electrons from the ground state of the quantum well into the continuum, causing a photocurrent. Three dark current mechanisms are also shown: ground state tunneling (1); thermally assisted tunneling (2); and thermionic emission (3).

Fig. 2 Comparison of dark currents of bound-to-continuum and bound-to-quasibound LWIR QW1 Ps as a function of bias voltage at temperature T = 70 K. Data were taken with a 200pm diam test structure and normalized to $28 \times 28 \mu m^2$ pi xel.

Fig. 3 Responsivit y spectrum of a bound-to-quasibound LWIR QWI P test structure at temperature T = 77 K. The spectral response peak is at 8.5 μm and the long wavelength cutoff is at 8.9 μm.

Fig. 4 Peak responsivity as a function of bias voltage at temperature T = 77 K.

Fig. 5 Detect ivity as a function of bias voltage at temperatures T = 70 and 77 K.

Fig. 6 (a) Intersubband absorption process of QWIPs at normal incidence. (b) 45° polished facet light coupling.

Fig. 7 (a) Two level random reflector on a pixel (38×38 μm^2) of 15 μm cutoff QWIP FPA. The **minimum feature size** is 1.25 pm. (b) Two level random reflector on a pixel (28×28 μm^2) of 9 pm cutoff QWIP FPA. The minimum feature size is 0.6 pm. This random reflector was less sharp and had fewer scattering centers when compared to Fig. 7(a) due to the difficulties associated with sub-micron photolithograph y.
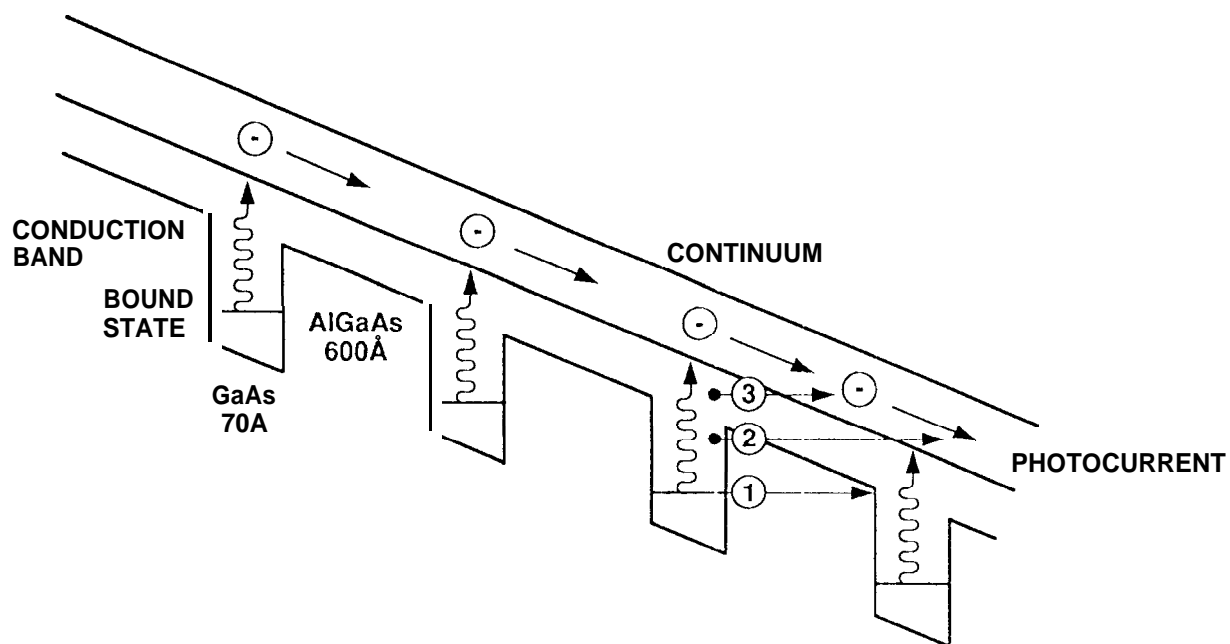
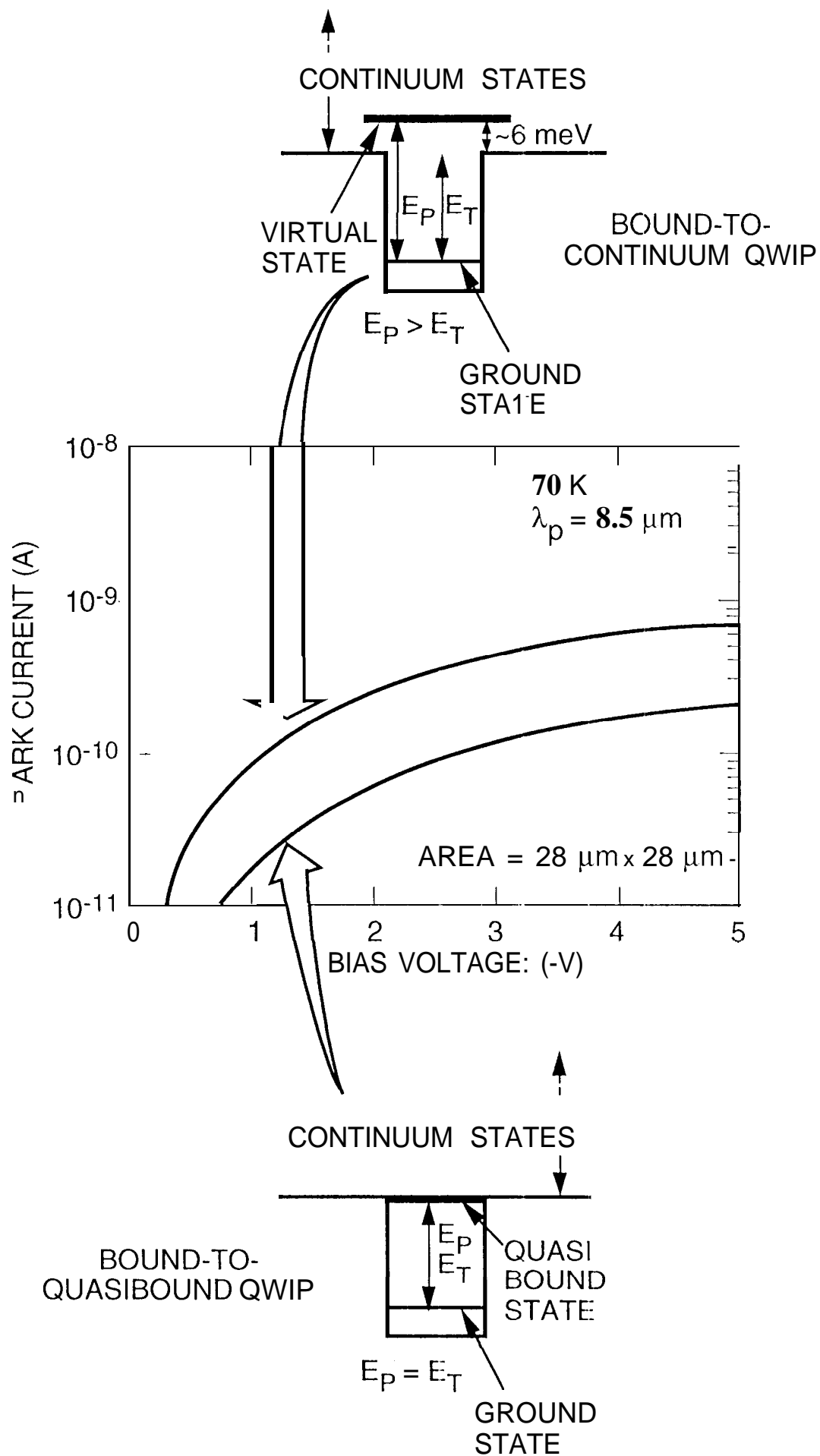Fig. 8 Twenty five 256x256 QW1 P focal plane arrays on a 3 in. GaAs wafer.

Fig. 9 Noise equivalent temperature difference NEAT estimated from test structure data as a function of temperature for bias voltages $V_B = -1$, -2, and -3 V. The
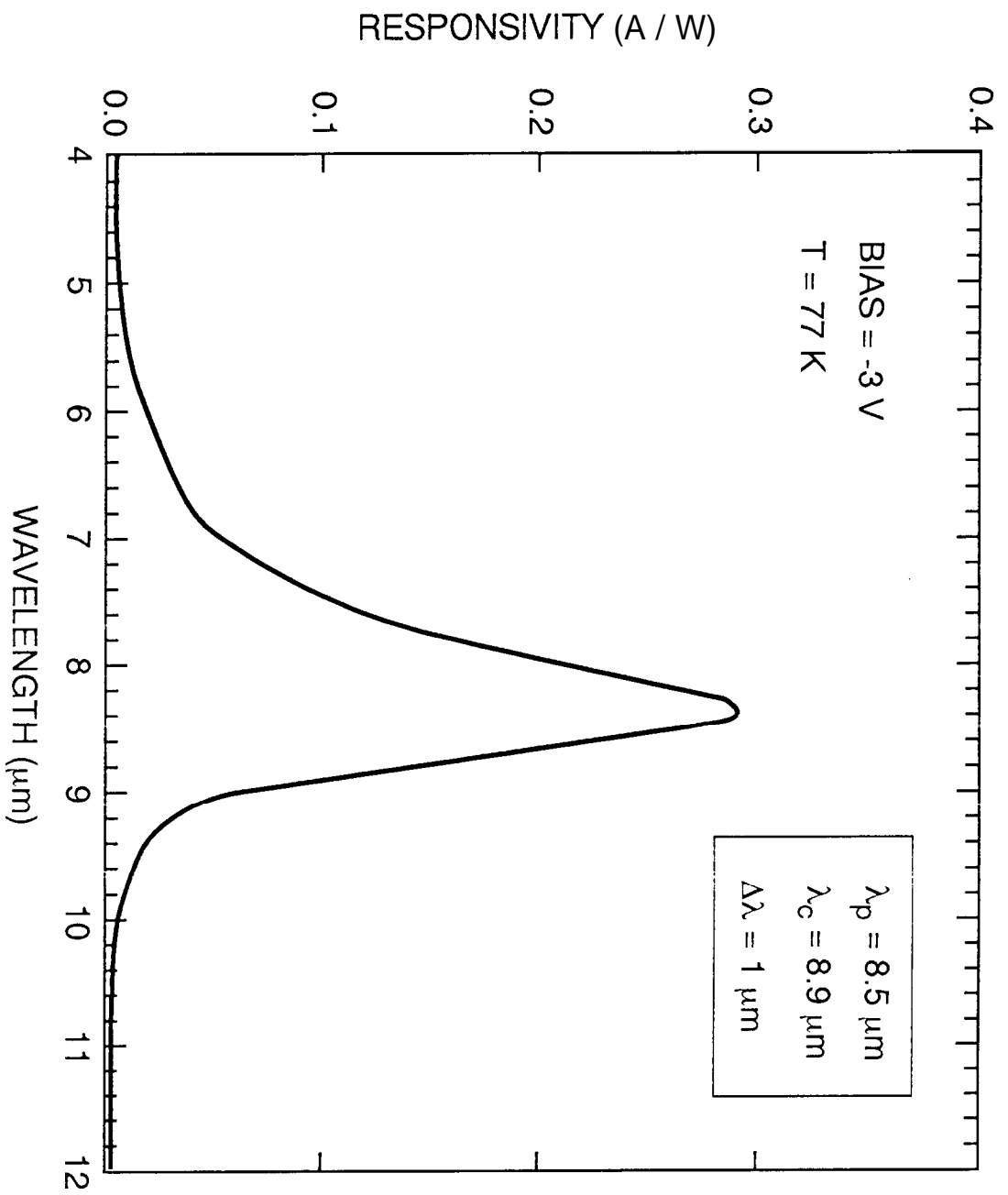
background temperature $T_B = 300$ K and the area of the pixel $A = (28 \ \mu m)^2$. The measured NEΔT of the focal plane array is 25 mK at an operating temperature of 70 K and bias $V_B = -1$ V.
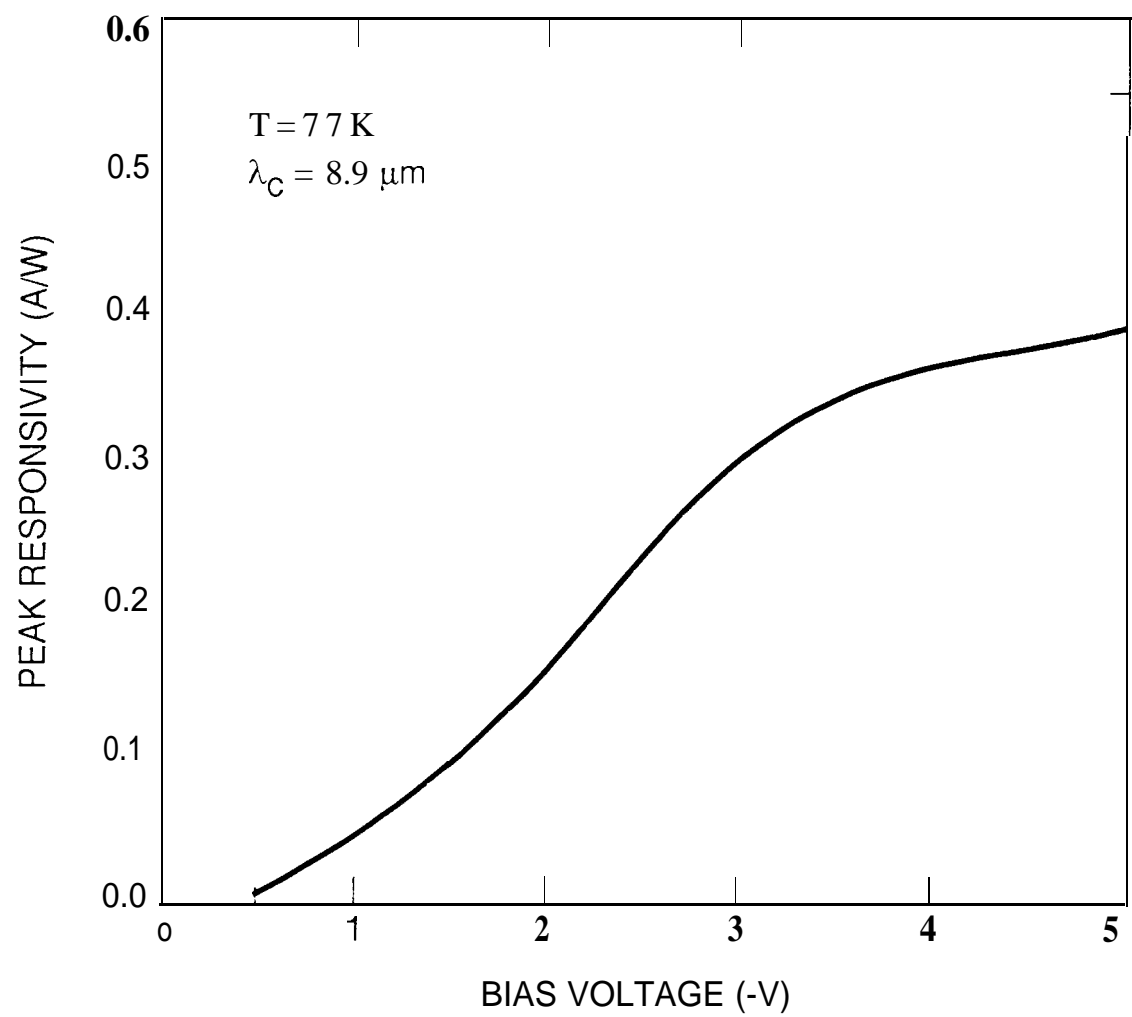
Fig. 10 Photosignal histogram of the 65,536 pixels of the 256x256 array showing a high uniformity of the FPA. The uncorrected non-uniformity ($=$ standard deviation/mean) of the FPA is only 6.8% including 1 % non-uniformity of ROC and 1.4% non-uniformity due to the cold-stop not being able give the same field of view to all the pixels in the FPA.
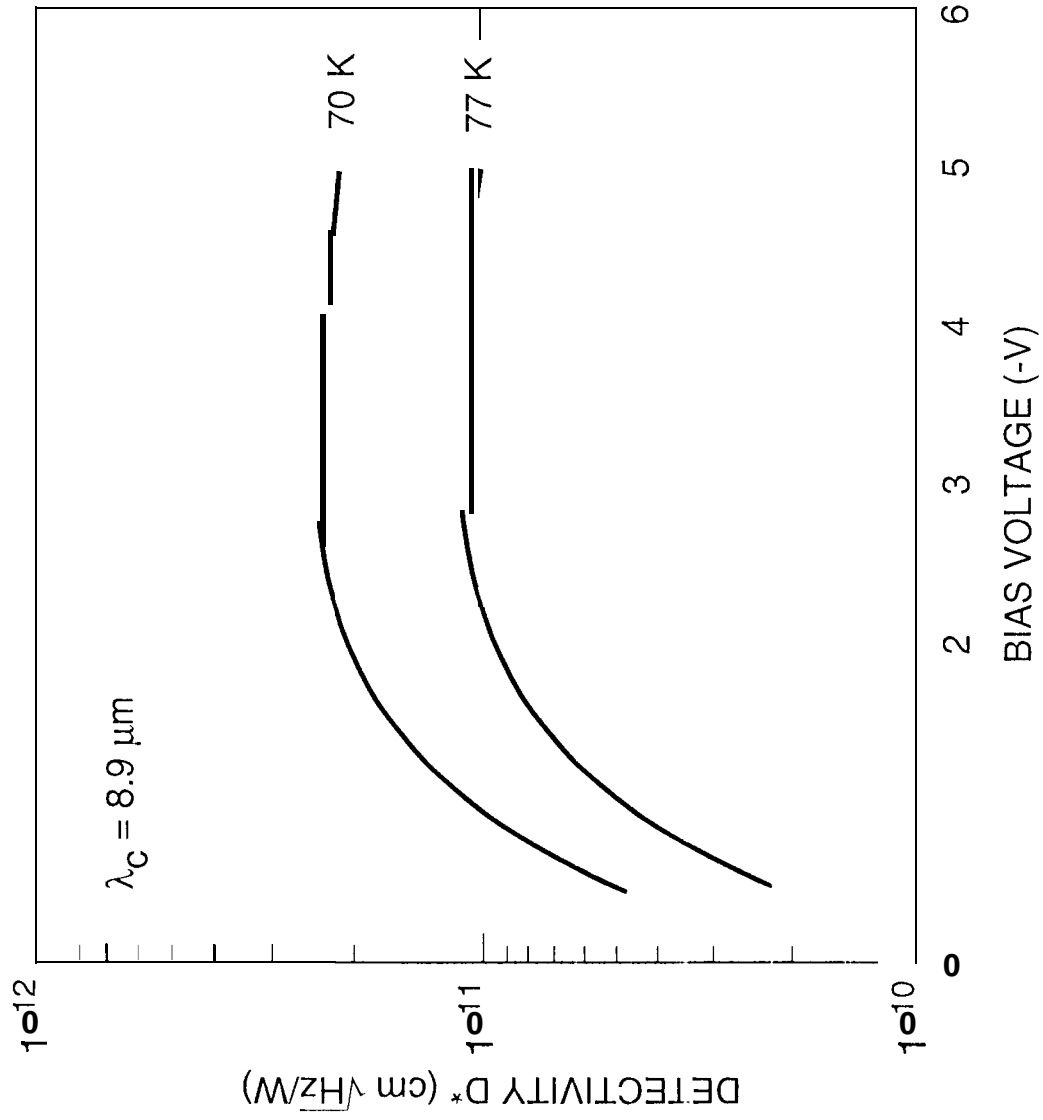
Fig. 1 **(a) One** frame of video image taken with the 9 μm cutoff 256x256 QWIP camera. The tiny dark squares on each frame of the glasses are the reflections of cold FPA in the camera. (b) An absorption image of acetone fumes (acetone has a strong IR absorption at 8.8 μm) taken with a 9 μm cutoff 256x256 QWI P FPA camera.
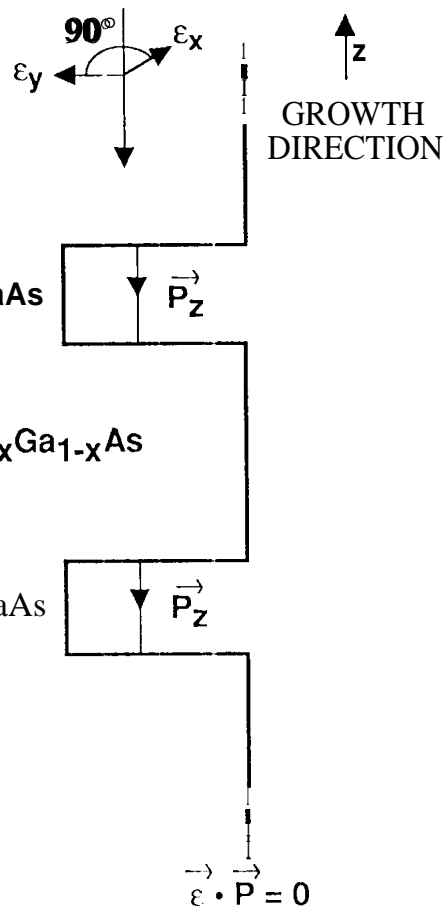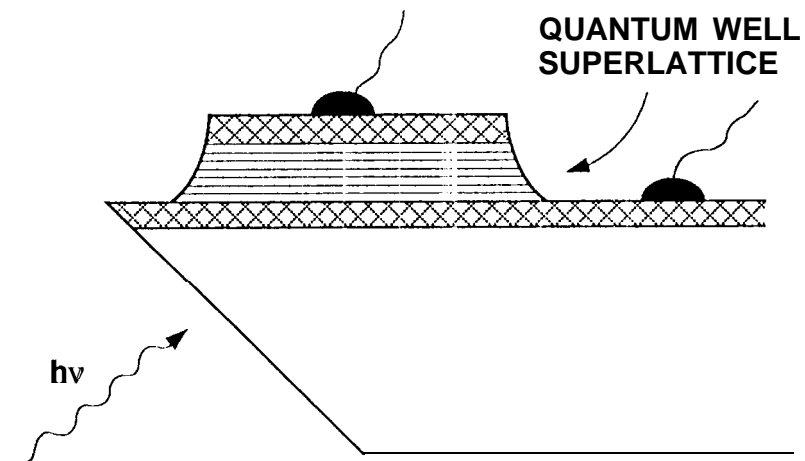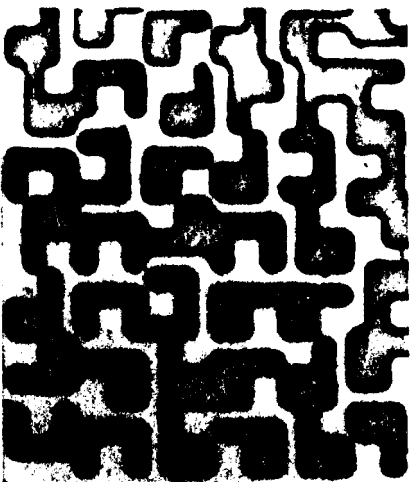
CONTINUUM STATES

~6 meV

E_P E_T

VIRTUAL
STATE

BOUND-TO-
CONTINUUM QWIP

$E_P > E_T$

GROUND
STATE

70 K
$\lambda_p = 8.5\ \mu m$

AREA = 28 μm x 28 μm

DARK CURRENT (A)

10^{-8}

10^{-9}

10^{-10}

10^{-11}

0   1   2   3   4   5

BIAS VOLTAGE: (-V)

CONTINUUM STATES

BOUND-TO-
QUASIBOUND QWIP

E_P
E_T

QUASI
BOUND
STATE

$E_P = E_T$

GROUND
STATE

RESPONSIVITY (A / W)

WAVELENGTH (μm)

BIAS = -3 V

T = 77 K

λ_p = 8.5 μm
λ_c = 8.9 μm
$\Delta\lambda$ = 1 μm

T = 7 7 K
λ_C = 8.9 μm

PEAK RESPONSIVITY (A/W)

BIAS VOLTAGE (-V)

(a)

IR
RADIATION

$90°$ ε_x

ε_y

z

GROWTH
DIRECTION

GaAs $\vec{P}_z$

$Al_xGa_{1-x}As$

GaAs $\vec{P}_z$

$\vec{\varepsilon} \cdot \vec{P} = 0$

(b)

**QUANTUM WELL
SUPERLATTICE**

$h\nu$

b

a

F#/2 OPTICS
FRAME RATE = 30 Hz

256 x 256 FOCAL
PLANE ARRAY
DATA

NE$_z$TD (mK)

-1 v BIAS

-2 v

-3 V

OPERATING TEMPERATURE (K)

a

b